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THESIS

STRIKE PACKAGE-TARGET PAIRING: REAL-TIME OPTIMIZATION FOR AIRBORNE BATTLESPACE COMMAND AND CONTROL

by

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September 2010

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When an air strike is requested against a target, the desired result is rapid arrival of a strike package of appropriately armed aircraft to destroy the target. However, the current manual system used by airborne battle managers is outdated, resulting in a slower strike package delivery time. This primitive system requires the operator to pair strike packages to targets manually in real time. A system that improves the efficiency of the airborne battle managers in a high-workload environment would result in faster strike package-target pairing and tasking, and might result in better parings. We develop a model, RASP, that creates strike package-target pairings that best satisfy operational requirements as outlined in various joint publications and clarified by Naval Strike and Air Warfare Center subject matter experts. RASP minimizes data entry while replicating the decision processes that military operators use to decide strike package-target pairings. The starting point for this thesis is the RAPT-OR model, developed by Zacherl in 2006, a weapon-target pairing tool we adapt for use in a real-time tactical decision aid for airborne battle managers.

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STRIKE PACKAGE-TARGET PAIRING: REAL-TIME OPTIMIZATION FOR AIRBORNE BATTLESPACE COMMAND AND CONTROL

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ABSTRACT

When an air strike is requested against a target, the desired result is rapid arrival of a strike package of appropriately armed aircraft to destroy the target. However, the current manual system used by airborne battle managers is outdated, resulting in a slower strike package delivery time. This primitive system requires the operator to pair strike packages to targets manually in real time. A system that improves the efficiency of the airborne battle managers in a high-workload environment would result in faster strike package-target pairing and tasking, and might result in better parings. We develop a model, RASP, that creates strike package-target pairings that best satisfy operational requirements as outlined in various joint publications and clarified by Naval Strike and Air Warfare Center subject matter experts. RASP minimizes data entry while replicating the decision processes that military operators use to decide strike package-target pairings. The starting point for this thesis is the RAPT-OR model, developed by Zacherl in 2006, a weapon-target pairing tool we adapt for use in a real-time tactical decision aid for airborne battle managers.

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LIST OF ACRONYMS AND ABBREVIATIONS

ABCC	Airborne Battlespace Command and Control
AOC	Air Operations Center
ASOC	Air Support Operations Center
ATO	Air Tasking Order
BDA	Battle Damage Assessment
CAS	Close Air Support
DASC	Direct Air Support Center
GBU	Guided Bomb Unit
GPS	Global Positioning system
HARM	High-Speed Anti-Radiation Missiles
INT	Airborne Interdiction
JDAM	Joint Direct Attack Munition
JFACC	Joint Forces Air Component Commander
JSTARS	Joint Surveillance Target Attack Radar System
JTAC	Joint Terminal Attack Controller
JTASR	Joint Tactical Air Strike Request
LGB	Laser Guided Bomb
MISREP	Mission Report
OIF	Operation Iraqi Freedom
RAPT	Rapid Asset Pairing Tool
RAPT-OR	Rapid Asset Pairing Tool-Operations Research
RASP	Rapid Air Strike Pairing
REDS	Real-Time Execution Decision Support
SAM	Surface-to-Air Missile
SCAR	Self Contained Armed Reconnaissance
SPAWAR	Space and Naval Warfare Systems Command
TACP	Tactical Air Control Party
TST	Time-Sensitive Target

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EXECUTIVE SUMMARY

Current air strike package-target pairing is a slow process that requires tremendous amounts of manual data processing. The processing is done using handwritten forms, which are passed between multiple operators. This process ensures that pairings are feasible and able to accomplish mission objectives. We develop a model, Rapid Air Strike Pairing (RASP), for optimal strike package-target pairing (or “pairing”) as outlined in various joint publications and clarified by Naval Strike and Air Warfare Center subject matter experts. RASP creates pairings that are optimal for quantitative evaluations of operational requirements. This thesis advocates minimizing data entry requirements while replicating the decision processes that military operators use to perform strike package-target pairing. The starting point for this thesis is the RAPT-OR model, developed in 2006 by Zacherl, providing a weapon-target pairing planning tool for use at the Air Operations Center staff level, focusing on rapid revisions to an air tasking order based on emergent time-sensitive targets; we adapt that model so that it can be used as a real-time tactical decision aid for airborne battle managers at the operational unit level.

When an air strike is requested against a target, the job of the airborne battle manager is to facilitate the rapid arrival of a strike package of appropriately armed aircraft to destroy the target. Airborne battle managers are often required to simultaneously carry out a variety of tasks that include moving and positioning aircraft in three dimensions, managing aerial refueling, pairing strike packages to targets, passing threat warnings, deconflicting airspace, maintaining theatre-level communications networks, and much more. Many distinct airborne and ground-based units from different services are capable of performing the Airborne Battlespace Command and Control (ABCC) mission, including the Marine Corps’s Direct Air Support Center (DASC), the Air Force’s Air Support Operations Center (ASOC), the Navy’s E-2C Hawkeye, the Air Force’s E-3 Sentry, and Air Force’s Joint Surveillance Target Attack Radar System (JSTARS).

Even when skilled operators are performing this mission, the high volume of information flowing to and from command-and-control nodes can create intense operator

processing requirements. These requirements constrain the speed at which strike aircraft are passed targeting information. Due to the sheer volume of considerations when pairing manually, even experienced operators sometimes make mistakes that result in poor pairings.

In addition to “good” target pairing, the ABCC mission requires *fast* target pairing. Even the perfect pairing of a strike package to a target is wasted if in making that pairing too much time is consumed. Each aircraft flying has a limited amount of fuel, and every minute wasted decreases the range at which an aircraft can support friendly forces. Another problem with the existing system is that different operators have different pairing systems and, as such, their pairings are inconsistent with each other. These inconsistencies can arise even when operators are looking at the same set of assets and targets.

Systems to replace the existing system, which are designed to perform strike package-target pairing down to the airborne battle manager level, have been developed. However, they have yet to be adopted by units responsible for strike package-target pairing. RASP takes a different approach; it duplicates the existing system while automating as much of it as possible.

We have developed the RASP decision aid to add to the current command and control structure. It will substantially improve the efficiency of the existing weapon target pairing system at the airborne battle manager level, and will have essentially zero incremental cost per seat because, with the implementation of code to solve network flow problems, it can be implemented in commercial off-the-shelf software already owned by these operational units.

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First, I thank my beautiful wife, Jessica, for her infinite patience and support throughout this process. As this project winds down, I am very much looking forward to spending more time with our new daughter, Sonia.

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I. INTRODUCTION

A. PURPOSE AND OVERVIEW

Current air strike package-target pairing is accomplished by a process that requires a significant amount of manual data processing on handwritten forms that are passed between multiple operators. At each step, the operators must ensure that pairings are feasible and accomplish the mission objectives. We develop an optimization model, Rapid Air Strike Pairing (RASP), for optimal strike package-target pairing (or, simply, "pairing") where a *package* is a set of armed aircraft available to strike *targets*, which are objects or areas identified for possible action to support the commander's intent. Here, we follow the definitions of joint publications (JCS 1994, 1997, 2001, 2002, 2003, 2009) as clarified by Naval Strike and Air Warfare Center subject matter experts (NBVC, 2009). RASP creates pairings that are optimal for quantitative evaluations of operational requirements, and it minimizes data entry requirements while replicating the decision processes that military operators use to perform strike package-target pairing. Zacherl (2006) provides a weapon-target pairing planning tool for the Air Operations Center (AOC), the command and control center of the Joint Forces Air Component Commander (JFACC), focusing on rapid revisions to an Air Tasking Order (ATO), the published plan in theatre that includes all air missions, tanking plans, communications, and assets. These revisions are sometimes necessary, because of the appearance of a time-sensitive target (TST), a target of such high priority that the Joint Force Commander designates it as requiring an immediate response because it poses a danger to friendly forces, or is a highly lucrative, fleeting target of opportunity (JCS, 2009). We adapt that model so that it can be used in a real-time tactical decision aid for airborne battle managers, the operators responsible for the execution of the command and control functions in Airborne Battlespace Command and Control (ABCC), which is the mission of performing command and control of aircraft in a theatre of operations.

Based on preliminary feedback from several members of the strike planning community, this tool will improve the ability of military operators to effectively manage

air-to-ground strike pairing in real time during major military campaigns of the scope and scale of Operation Desert Storm and the opening phases of Operation Iraqi Freedom (OIF).

B. BACKGROUND

1. Problem Statement

In a modern theatre of war, airborne battle management requires a highly skilled group of operators capable of performing under intense workloads. In a theatre of operations, the operators that are responsible for pairing strike packages to targets are known as airborne battle managers. When an air strike is requested against a target, the job of the airborne battle manager is to facilitate the rapid arrival of a strike package of appropriately armed aircraft that can destroy the target. Airborne battle managers are often required simultaneously to move and position aircraft in three dimensions, manage aerial refueling, pair strike packages to targets, pass threat warnings, deconflict airspace, maintain theatre-level communications nets, and much more. Even when skilled operators are available, the high volumes of information flowing to and from command and control nodes can create intense operator processing requirements, which can constrain the speed at which strike aircraft are passed targeting information. Heavy operator workload within the command and control node can cause delays in the total processing time of these requests that are often excessive, only rarely are these delays the result of a lack of appropriate strike aircraft or proper weapons (NBVC, 2009).

Many distinctive airborne and ground-based units from different services are capable of performing the ABCC mission. In a joint theatre, airborne battle management units from various services are generally interchangeable; the JFACC will normally designate a unit that has the primary ABCC mission and a unit that is secondary, in the event the primary unit is unable to perform the mission. ABCC doctrine has been standardized across the services; capable units include the Marine Corps's Direct Air Support Center (DASC), the Air Force's Air Support Operations Center (ASOC), the Navy's E-2C Hawkeye, the Air Force's E-3 Sentry, and Air Force's Joint Surveillance Target Attack Radar System (JSTARS). For example, during the opening phases of OIF,

the DASC was responsible for supporting the Marine advance in the Eastern half of Iraq, and the ASOC was responsible for supporting the Army advance in the West. Both the ASOC and the DASC seamlessly coordinated Army and Marine helicopters, carrier-based Navy aircraft, British attack aircraft, and many other units.

The cost of delays in the coordination of air strikes can be steep; a high-value time-sensitive target may have time to escape, friendly ground forces could be overrun, and hostile missiles and aircraft could be launched. However, the systems that the units performing airborne battle management use to pair strike packages to targets are primitive.

Manual strike package-target pairing means that an operator reads the list of strike packages from a piece of paper and the list of targets from a separate piece of paper as they are passed back and forth between operators, and evaluates the factors necessary to make a good pairing. These factors include *loadouts* (the ordinance carried by an aircraft), *playtime* (the time an aircraft has available to be assigned to a target before it has to return to base, for reasons such as low fuel or assigned landing times), stand-off range of weapons, speed of the aircraft, weapon probability of kill, whether the target is moving or stationary, and mission suitability. Due to the sheer volume of considerations when pairing even a few missions and targets, even experienced operators sometimes make mistakes that result in poor pairings, and may even make pairings that have no chance of resulting in successful target destruction. For example, operators in simulators have paired aircraft armed with Joint Direct Attack Munitions (JDAM), a GPS-guided bomb, against moving targets. Unfortunately, JDAM is useless against moving targets. A bad pairing could result in a strike package flying hundreds of miles over hostile territory, only to realize that it is useless and low on gas upon arrival at its target. If the aircraft in the package have inadequate fuel, it must return directly without accomplishing the mission.

Another problem with the existing system is the lack of consistency between pairings made by different operators looking at the same set of assets and targets (NBVC, 2009 and NSAWC, 2010). While the values assigned to factors in ABCC are defined by joint doctrine, the relative weightings of those factors are not defined (JCS 2009). In

practice, this lack of a standard system results in priorities being defined on-the-fly by the operator making the pairing. One operator may believe that it is more important to use the asset with only five minutes of playtime remaining, while another operator might think that a short distance from a strike package to the target should take priority over playtime remaining. Under the current system, both operators have valid evaluations of the situation. The vastly different pairings that result from the respective systems used by different operators means that commanders cannot be sure how operators are going to make pairings. This becomes an important issue, especially when inexperienced operators make pairings poorly, because the commander is unable to conclude that these decisions are poor based on doctrine alone.

The existing process, where airborne battle managers manually pair strike packages to targets, is time consuming, operator intensive, and prone to error and inconsistency. Therefore, a system that maintains experienced operator control while automating most aspects of strike package-target pairing resulting in strike packages arriving at targets more efficiently would be valuable, especially in a high workload environment.

C. HISTORY OF STRIKE PACKAGE-TARGET PAIRING

Previous tools such as RAPT and RAPT-OR are designed to reassign strike packages to time-sensitive targets with minimum disruption to the Air Tasking Order (ATO) at the Air Operations Center (AOC) level. RASP is designed to manage the entire airborne battle in real time by airborne battle managers. Airborne battle managers are subordinate to the AOC and are tasked by the AOC to perform the ABCC mission. Tools such as RAPT and RAPT-OR are not designed to be used at the Airborne Battle Manager level and would be ineffective if used in the execution of the ABCC mission.

REDS (Real-time Execution Decision Support) is a system developed primarily by SPAWAR (Space and Naval Warfare Systems Command) (McDonnell and Gizzi, 2003) that attempts to take large amounts of data and minimize the operator workload. However, REDS is not in use by any Airborne Battle Management unit. REDS requires a huge amount of data management, making it unsuitable for any level of command and

control below the AOC without extensive systems integration, which has yet to occur. The fundamental problems with REDS is that the data input requirements on the part of the operator are unmanageable in real-time. It is often more efficient for operators to pass essential data elements on handwritten papers back and forth, rather than manage large amounts of unnecessary data in a computer. In the future, it may be possible to have the required data automatically fed into such a system through networks and data links. However, no such system exists today (NSAWC 2010).

D. THESIS ORGANIZATION

Chapter II provides a detailed description of ABCC units, the existing mission request processes, and the weaknesses of those processes. Chapter III describes the RASP optimization model. Chapter IV provides the computational results of RASP through the analysis of a hypothetical operational scenario. Chapter V presents conclusions and other potential uses of the model.

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II. STRIKE PACKAGE-TARGET PAIRING IN AIRBORNE BATTLESPACE COMMAND AND CONTROL

A. INTRODUCTION

The pairing of strike packages to ground targets is not a new concept in warfare. Aerial bombing coordinated by radio has been a common component of warfare since the 1930s. However, although most tasking is still performed by radio, increased communication and sensor ranges continue to increase the workload on operators responsible for managing the real-time ABCC elements of the Air Tasking Order (ATO). The ABCC mission is highly dynamic; an operator may be responsible for the simultaneous real-time management of aircraft assigned to close air support, airborne interdiction (INT) (the mission of attacking enemy forces using air power at a distance from friendly forces), self-contained armed reconnaissance (SCAR), airborne tanking, ground alerts, and a host of other missions.

B. CLOSE AIR SUPPORT AND TIME-SENSITIVE TARGETS

To understand the decisions of the ABCC operator, it is important not only to understand how strike packages are paired to targets, but the procedures used to make those pairings. There are two primary methods that targets are generated for the ABCC operator; targets can be passed through the kill chain, the sequence of steps from target sighting to target destruction we describe below, or time-sensitive targets can be passed directly from the AOC. All the various missions that fall under the ABCC umbrella come from one of these two sources.

For an example of a standard kill chain notification, let us assume that hostile enemy tanks have been spotted by Marine reconnaissance. The Marines have a joint terminal attack controller (JTAC), an operator controlling close air support during joint combat operations, who passes targeting information to the tactical air control party (TACP), a team of command and control specialists who advise the ground commander on the best use of air power, via the briefing format (JCS, 2009) for close air support (CAS), a mission to strike targets in close proximity to friendly ground forces. That

information is then passed to the Air Support Operations Center (ASOC), the Air Force unit that is a clearing house for air support requests and is where strike package-target pairings are usually made, and incorporated into a joint tactical air strike request (JTASR), the standardized document on which the status of all CAS requests are tracked. Figure 1 is a reproduction of a JTASR form. It includes a section (box 8) referred to by operators as the "9-line" procedure, which contains the nine pieces of critical target information. In contrast to CAS procedures, to prosecute an emergent TST, this set of nine critical pieces of information is passed informally through means other than a standard JTASR.

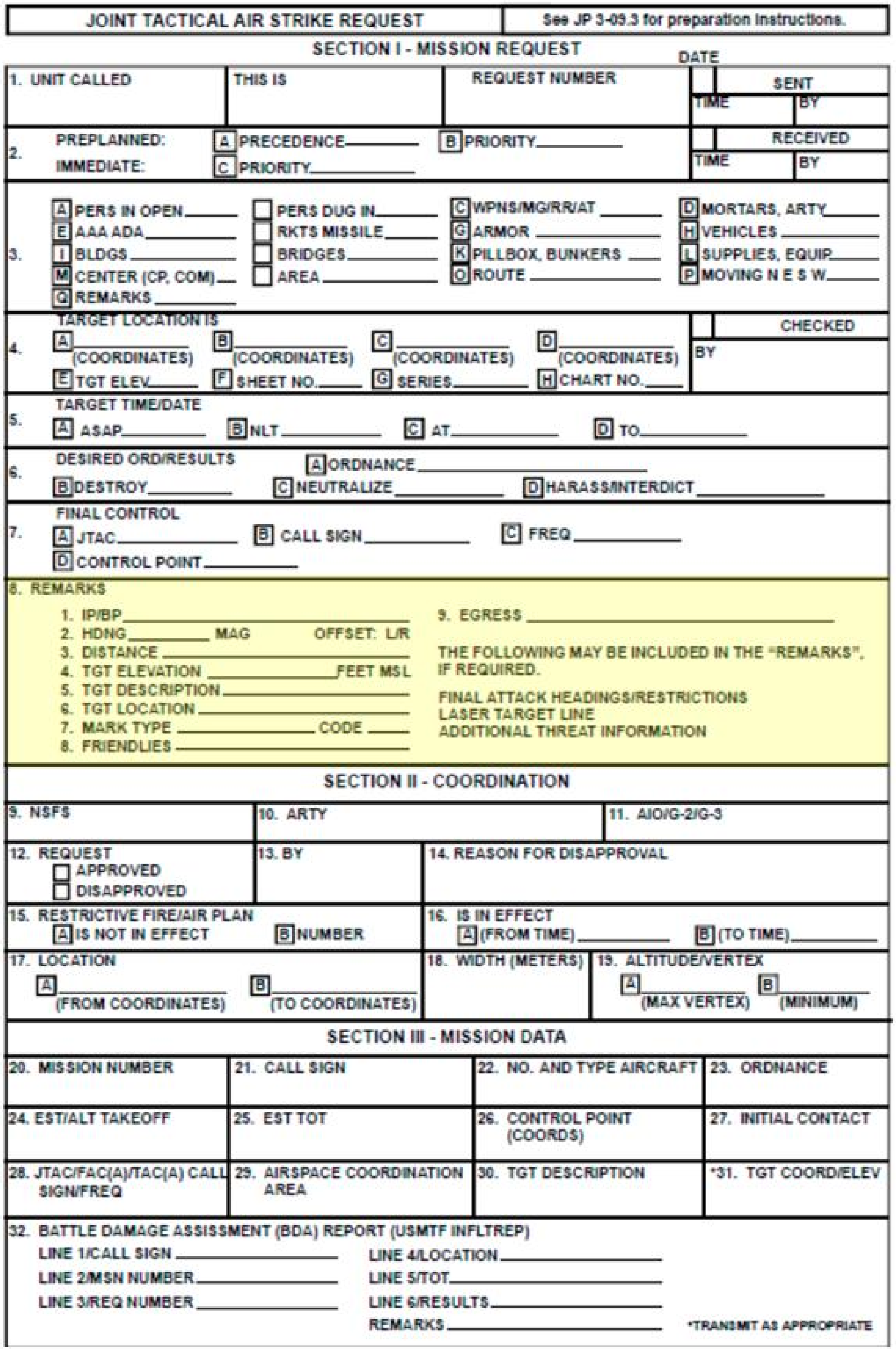
JOINT TACTICAL AIR STRIKE REQUEST
See JP 3-09.3 for preparation instructions.
SECTION I - MISSION REQUEST
DATE
1. UNIT CALLED
THIS IS
REQUEST NUMBER
SENT
TIME
BY
2. PREPLANNED: A PRECEDENCE____ B PRIORITY____
IMMEDIATE: C PRIORITY____
RECEIVED
TIME
BY
3. A PERS IN OPEN____ PERS DUG IN____ C WPNS/MG/RR/AT____ D MORTARS, ARTY____
E AAA ADA____ RKTS MISSILE____ G ARMOR____ H VEHICLES____
I BLDGS____ BRIDGES____ K PILLBOX, BUNKERS____ L SUPPLIES, EQUIP____
M CENTER (CP, COM)____ AREA____ O ROUTE____ P MOVING N E S W____
Q REMARKS____
4. TARGET LOCATION IS
A____ (COORDINATES) B____ (COORDINATES) C____ (COORDINATES) D____ (COORDINATES)
E TGT ELEV____ F SHEET NO.____ G SERIES____ H CHART NO.____
CHECKED
BY
5. TARGET TIME/DATE
A ASAP____ B NLT____ C AT____ D TO____
6. DESIRED ORD/RESULTS
A ORDNANCE____
B DESTROY____ C NEUTRALIZE____ D HARASS/INTERDICT____
7. FINAL CONTROL
A JTAC____ B CALL SIGN____ C FREQ____
D CONTROL POINT____
8. REMARKS
1. IP/BP____
2. HDNG____ MAG OFFSET: L/R
3. DISTANCE____
4. TGT ELEVATION____ FEET MSL
5. TGT DESCRIPTION____
6. TGT LOCATION____
7. MARK TYPE____ CODE____
8. FRIENDLIES____
9. EGRESS____
THE FOLLOWING MAY BE INCLUDED IN THE "REMARKS", IF REQUIRED.
FINAL ATTACK HEADINGS/RESTRICTIONS
LASER TARGET LINE
ADDITIONAL THREAT INFORMATION
SECTION II - COORDINATION
9. NSFS
10. ARTY
11. AIO/G-2/G-3
12. REQUEST
APPROVED
DISAPPROVED
13. BY
14. REASON FOR DISAPPROVAL
15. RESTRICTIVE FIRE/AIR PLAN
A IS NOT IN EFFECT B NUMBER
16. IS IN EFFECT
A (FROM TIME)____ B (TO TIME)____
17. LOCATION
A____ (FROM COORDINATES) B____ (TO COORDINATES)
18. WIDTH (METERS)
19. ALTITUDE/VERTEX
A____ (MAX VERTEX) B____ (MINIMUM)
SECTION III - MISSION DATA
20. MISSION NUMBER
21. CALL SIGN
22. NO. AND TYPE AIRCRAFT
23. ORDNANCE
24. EST/ALT TAKEOFF
25. EST TOT
26. CONTROL POINT (COORDS)
27. INITIAL CONTACT
28. JTAC/FAC(A)/TAC(A) CALL SIGN/FREQ
29. AIRSPACE COORDINATION AREA
30. TGT DESCRIPTION
*31. TGT COORD/ELEV
32. BATTLE DAMAGE ASSESSMENT (BDA) REPORT (USMTF INFLTREP)
LINE 1/CALL SIGN____ LINE 4/LOCATION____
LINE 2/MSN NUMBER____ LINE 5/TOT____
LINE 3/REQ NUMBER____ LINE 6/RESULTS____
REMARKS____
*TRANSMIT AS APPROPRIATE

Figure 1. A Joint Tactical Air Strike Request (JCS, 2009). This is the standard format for a CAS request, and includes all the target information and airborne battle manager would need to make a pairing from available aircraft. Every request is filled out completely. We have highlighted a section referred to as the "9-line procedure," by operators.

The operators in the ASOC, who are generally responsible for tasking CAS aircraft in a joint or combined theatre, are responsible for prioritizing the target and assigning a strike package from available strike packages. The assigned strike package then contacts the JTAC and strikes the tanks. Battle damage assessment (BDA), an evaluation of the target after an air strike is completed, is performed and a mission report (MISREP), a report from the lead pilot to the commander regarding target and mission status, is passed; see Figure 2.

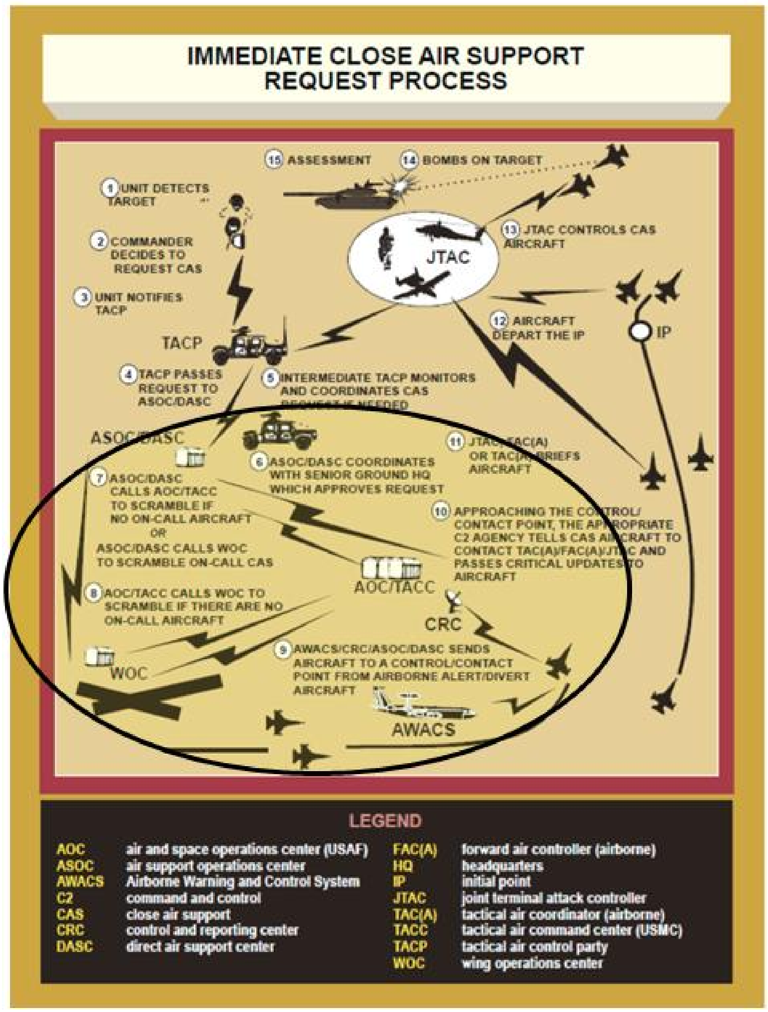

Figure 2. The Immediate Close Air Support Request Process (JCS, 2009). This thesis focuses on the Air Support Operations Center (ASOC) and Direct Air Support Center (DASC) portion of the CAS request process because it is within these types of units that strike package-target pairings are made. Here, these portions are contained within steps six through ten (circled).

The time-sensitive target (TST) process is different from the CAS process. TSTs can come from many different sources, from ground-based operators to patrolling aircraft. TSTs may also be passed directly from the AOC. TSTs are not generally passed using 9-line procedures and may or may not have specific aircraft already assigned to their tasking. TSTs can be very high-priority tasking; the strike on the suspected location of Saddam Hussein, which started OIF, was passed to strike aircraft via a TST.

C. THE ROLE AND RESPONSIBILITY OF AIRBORNE BATTLESPACE COMMAND AND CONTROL

During an ABCC mission, operators are responsible for manually pairing strike packages to targets. Operators within the units executing the ABCC mission have many factors to take into account when pairing of strike packages and targets. Operators must consider the playtime of the strike package, the distance of each strike package from the target, the *priority* (stated as an integer between one and three inclusive, one being the highest priority for the commander) of each target, the *precedence* (stated as an integer between one and thirty inclusive, one being the highest priority for the requestor) of each target, weapon capability against the target, number of weapons versus number of targets, the assigned mission of the strike package, target location relative to surface to air missiles (SAMs), and many others. In addition, there is no standard formula that ABCC operators use to weigh these factors when making their decisions although there are some rules. For example, priority dominates precedence; a target with priority two, precedence thirty is considered more important than a target with priority three, precedence one, with all other factors being equal. In order to resolve situations that are not clear cut, each operator develops his or her own system. Therefore, the quality of strike package to target pairing within a theatre of war is generally dependent on the skill and experience of the operator executing ABCC, and can vary greatly between operators (JCS, 2009).

In addition to “good” target pairing, of course ABCC requires *rapid* target pairing. The quality of a pairing is meaningless if it takes too long and the opportunity disappears.

D. WEAKNESSES OF EXISTING STRIKE PACKAGE-TARGET PAIRING PROCESSES

Despite the clear necessity for accurate and fast ABCC tasking, the existing systems to execute ABCC tasking are primitive. Within the units responsible for strike package to target pairing, the system (though it can vary in execution) generally works something like this: An operator (or two) is receiving target data passed manually via radio communications, potentially from multiple sources. The target data is written manually, usually on a piece of paper. The same operator can then plot the target, on a paper or electronic map, to ensure it is outside enemy SAM defenses. While these targets are arriving, a different operator is checking in strike packages and assigning them to *holding points* (locations aircraft are positioned at while waiting for tasking) in anticipation of targets. Once a target's data has been recorded, the piece of paper is passed to the operator responsible for the strike package to target pairing. That operator reads the target information, consults his available packages, weighs the previously discussed factors mentally, and makes a pairing. The operator checking in the packages is then passed the target information and tasks the chosen strike package to the target via the radio. The strike package executes the mission, checks back in to pass a MISREP (and most importantly, if re-attack is required). The strike package can then be assigned another target if they have additional playtime and ordinance, or they can return to base. The original paper is then passed back to the operator who first recorded the target information so that the MISREP from the strike package can be passed to the appropriate unit via radio.

Because a single operator is generally responsible for all strike package to target pairings, heavy traffic volume can prevent rapid tasking. Even without heavy traffic, making pairings requires an operator to consider several factors for each possible pairing, making the process difficult and time consuming. In an experiment, we provided an ABCC subject matter expert with a simple scenario with five missions and four targets, and it took him four minutes to pair those missions to the targets (NSAWC, 2010). This process often slows exponentially with more targets because the operator responsible for

pairing has exponentially more factors to compare before making a decision. Also, because time is often so critical in the pairing process, operators of all skill levels sometimes make poor pairings.

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III. RASP OPTIMIZATION MODEL FOR STRIKE PACKAGE-TARGET PAIRING

A. AN INTEGER LINEAR PROGRAM TO OPTIMIZE STRIKE PACKAGE-TARGET PAIRING

The RASP model combines available missions with available targets to form a set of potential strike packages. The model then assigns a "reward" to each strike package. The following mixed integer linear program, Rapid Air Strike Pairing, generates the best available pairings of strike packages to targets based on operator inputs.

B. SCOPE AND LIMITATIONS

RASP is intended to support pairings in a theatre of operations at the airborne battle manager level in real time. However, RASP could also be used for making pairings above this level, at the AOC for example, for both the planning of the ATO and its execution in real time.

RASP takes as input from operators in real time: the available aircraft positions weapons, mission type, and playtime, and available target positions, commander's priority, target type, and requestor's precedence. Positions will generally be entered as the position of the assigned holding point of the mission, not the exact position of the actual mission; this eliminates the need to constantly update all aircraft positions which would be unmanageable without extensive data link integration. RASP also takes the following inputs prior to the start of the mission: weapon standoff ranges, aircraft speeds, and weapon to target kill probabilities.

To calculate the probability of a kill when a platform carries multiple weapon types, RASP only considers the best weapon for the target under consideration (based on the probability of kill of the available weapons and the numbers of each weapon carried). A flight with multiple weapons may have a higher probability of kill than RASP considers because of the additional weapons it carries.

RASP can only assign one mission to one target. There could be scenarios where it would be better to pair two or more missions to a single target to achieve a certain probability of kill (Pk). RASP is currently unable to do this.

Our ability to test RASP up to this point has been limited. Simulators, and even large air war training scenarios such as Air Wing Fallon (Navy) or Red Flag (Air Force), would be the best opportunity for testing. However, even these scenarios pale in intensity compared to the major combat operations that RASP is designed to support.

1. Sets

$t \in T$ target type

$a \in A$ aircraft type

$w \in W$ weapon type

$m \in M$ a flight of aircraft

$(m, w, t) \in P \subseteq M \times W \times T$

package of aircraft, represented by a flight *m* with weapons *w* assigned to target *t*, corresponding to a *feasible* pairing (as defined below)

2. Data

$priority_t$ commander's priority for target *t*: 1, 2, or 3

$precedence_t$ requestors precedence for *t*: 1 to 30, 1 for TST

$num\_weapons_{mw}$ number of weapons in flight *m* of type *w*

$num\_targets_t$ number of targets within target *t*: ex. 7

$prob\_kill_{wt}$ probability of kill of weapon *w* against target *t*

$distance_{mt}$ distance of flight m from target *t* (nm)

$playtime_m$ playtime remaining for flight *m* (min)

$range_w$ standoff range of weapon *w* (nm)

$mission\_type_m$	the mission type *m*: cas=1, xcas=1, int=2, xint=2, etc.
$target\_type_m$	the mission type required by *t*: cas=1, xcas=1, int=2, xint=2, etc.
$standoff_t$	the minimum distance away from target *t* that is outside the range of any air defenses around *t* (nm)
$time\_to\_tgt_{mt}$	time of flight m to target *t* (min)
$speed_m$	the cruise speed of aircraft in mission *m* (kts)

3. Calculated Data

The set P is determined from the data; a tuple (m,w,t) is in P if and only if $mission\_type_m$ = $mission\_type\_req_t$, $range_w \geq standoff_t$, and $time\_to\_target_{mt} \leq 2*playtime_m$.

$time\_to\_tgt_{mt}$ The time to target in minutes based on speed and distance

$$= 60 * distance_{mt} / speed_m$$

$$reward_{mwt} = (100 - (30 * (priority_t - 1)) - precedence_t)$$
$$*(1-(1-prob\_kill_{wt})^{num\_weapons_{mw}/num\_targets_t})$$
$$*100 * e^{(-0.05 * time\_to\_tgt_{mt})} * 100 * e^{(-0.1 * playtime_m)}$$

4. Variables

$STRIKE_{mwt}$	1 if the strike is chosen, 0 otherwise

5. Formulation

$$\max_{STRIKE} \sum_{(m,w,t)\in P} reward_{mwt} STRIKE_{mwt} \qquad (0)$$

$$s.t. \quad \sum_{\substack{(m,w):\\(m,w,t)\in P}} STRIKE_{mwt} \leq 1 \qquad \forall t \in T \qquad (1)$$

$$\sum_{\substack{(w,t):\\(m,w,t)\in P}} STRIKE_{mwt} \leq 1 \qquad \forall m \in M \qquad (2)$$

$$STRIKE_{mwt} \in \{0,1\} \qquad \forall (m,w,t) \in P \qquad (3)$$

6. Discussion

The objective function (0) calculates the total reward from all pairings made. Each constraint (1) ensures that a target has at most one package assigned to it. Each constraint (2) ensures that no more than one mission is assigned to a strike package. The simple structure of the RASP model allows operators to require the model to make any pairing (or set of pairings) that they determine is required, by fixing the value of the appropriate $STRIKE_{mwt}$ variable(s) to one. The model will then optimally pair the remaining (i.e., unpaired) missions to targets. Such "required" pairings lead to a restriction of the original model that can yield solutions with lower total reward value than a solution with no required pairings. The model solves instantaneously, since it is essentially a network flow problem.

7. Reward Coefficients

Each reward coefficient provides a numerical value for a specific flight and target pairing, with higher reward values representing more desirable pairings. The first term, $(100-(30*(priority_t-1))-precedence_t)$, will have a value between 10 and 99 and gives a higher reward for targets that the commander designates as high priority and the requestor designates as high precedence. This formula guarantees that priority always dominates precedence, in that a unit change in priority cannot be completely counteracted by any change in precedence.

The second term, $(1-(1-prob\_kill_{wt})^{num\_weapons_{mw}/num\_targets_t})$, assumes weapons kill targets with the same probability, and independently, that only one successful hit is required to kill each target, and that we move on to the next target as soon as the previous one is killed. It will have a value between 0 and 1 and calculates the expected fraction of target kills for a given number of weapons of type *w* against a number of targets of type *t*. Generally, more weapons increases the reward for a given target. However, the marginal value of one additional weapon on a particular set of targets is decreasing in the number of weapons, and therefore the model will avoid overkilling targets if better pairings exist.

The next term $100 * e^{(-0.05 * time\_to\_tgt_{mt})}$ will be between zero and 100 and gives a higher reward the faster an aircraft can get to a target. Aircraft that are close to the target or speedy get a higher reward than farther away or slower aircraft.

The final term, $100 * e^{(-0.1 * playtime_{m})}$ will be between 0 and 100 and also rewards aircraft that are running out of playtime because it is more desirable to use an aircraft that must return to base anyway (for example, because it is running out of fuel) rather than an aircraft that is available for the next several hours.

The result of this calculation is a number between zero and 990,000, with larger rewards indicating better pairings. The actual values of the reward coefficients have no absolute interpretation; it is their values relative to each other that drive the model to make better pairings.

We present this objective function as an example, but welcome policy changes that would modify any aspect here. The idea is to arrive at some standard for pairing selection, and then following this, subject to manual override due to operator judgment.

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IV. COMPUTATIONAL RESULTS

To validate the strike-package target pairings made by RASP, we compare model solutions carried out on a Core i7™ MacBook Pro™ running the Windows 7™ OS.

A. TEST SCENARIO

The initial test scenario involves a hypothetical conflict on the Korean Peninsula where five strike packages are available to be matched with four targets (see Figure 3). Kill probabilities in this scenario are made up and weapon and air defense ranges (enemy SAMs include SA-2 Guidelines, SA-3 Goas, and SA-6 Gainfuls) are from Wikipedia. The various weapons (AGM-65 Mavericks, AGM-88 High-Speed Anti-Radiation Missiles (HARM), GBU-16 laser guided bombs (LGB), and GBU-32 JDAM) and carried by the strike package aircraft (A-10 Warthogs, F/A-18C Hornets, F-16 Falcons, F/A-18F Hornets, and E/A-6B Prowlers) have made-up probabilities of kill associated with each target (see Figure 3. and Figure 4).

MISSION #	CALLSIGN	TYPE	LOADOUT	LOADOUT	PLAYTIME	MISSION
M1	LONGHORN 31	2XA10	3XAGM65	2XGBU16	120	INT
M2	TROJAN 13	2XFA18C	2XGBU32		15	CAS
M3	COWBOY 41	2XF16	2XGBU32		45	INT
M4	SPARTAN 23	2XF18F	2XGBU16		25	CAS
M5	TARHEEL 38	1XEA6B	2XAGM88		60	SEAD
TARGET #	NAME	PRIORITY	PRECEDENCE	NUMBER	DESCRIPTION	
T1	JTAR 0611	1	10	4	TRUCKS (MOVING)	
T2	JTAR 0613	2	20	6	TANKS IN REVETMENTS	
T3	TST-CAVE	1	1	1	DEAR LEADER	
T4	SA-2	1	1	1	SA-2	

Figure 3. Scenario Strike Packages and Targets. In this scenario, five strike packages are holding with a variety of weapons, missions, and playtimes. Four targets are available with a variety of requirements, such as different standoffs and missions. For example, M1 is the first mission listed and consists of a pair of A-10 Warthog aircraft with AGM-65 Mavericks and GBU-16 LGB, a playtime of 120 minutes, and a mission of INT. T2 consists of 6 tanks in revetments with a commander's priority of 2 and a requestor's precedence of 20.

	MOVING TRUCKS	TANKS IN REVETMENTS	CAVE	SA-2
AGM65	0.8	0.6	0.5	0.7
GBU16(LGB)	0.9	0.7	0.6	0.9
GBU32(JDAM)	0	0.5	0.4	0.6
AGM88	0	0	0	0.6

Figure 4. Probability of Kill for Each Given Weapon and Target. This matrix shows the kill probability for each weapon against each target available in the given scenario.

A visual representation of the holding points, aircraft, and targets in the example scenario are depicted in Figure 5.

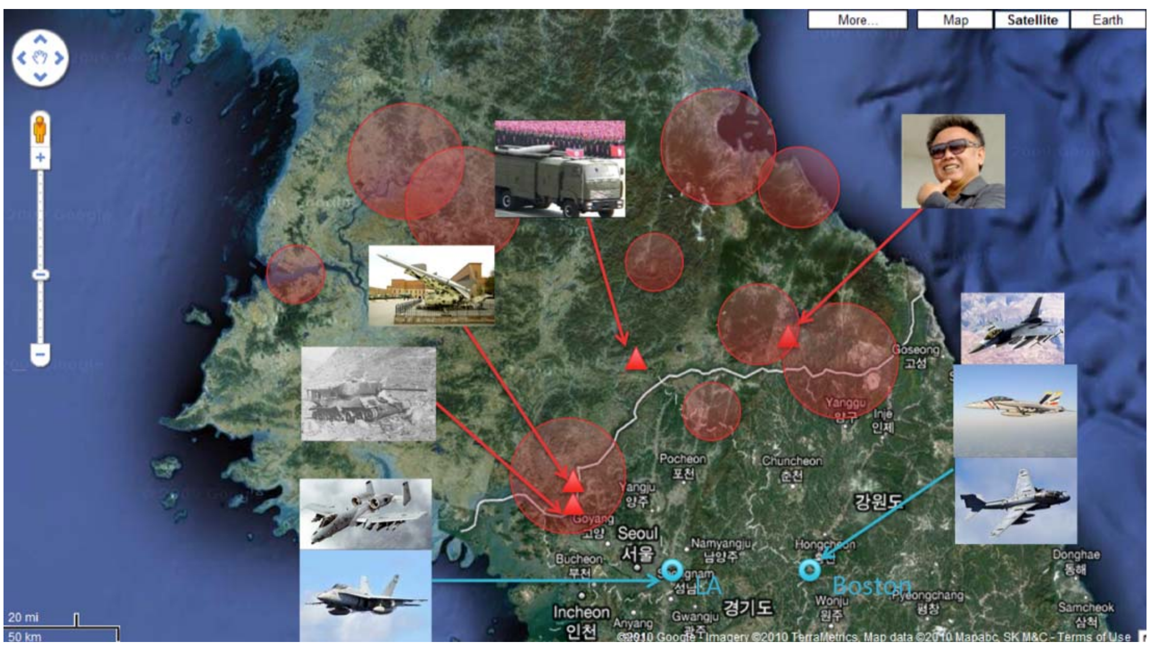

Figure 5. Visual Representation of the Scenario. The circles represent SA-2, SA-3, and SA-6 SAMs. The friendly aircraft are holding at points LA and Boston while standing by for tasking. The pictures match up to the packages and targets in Figure 3.

A run of the model under this scenario pairs the two A-10s (M1) with the cave (T3), two F/A-18Fs (M4) with moving trucks (T1), and the Prowler (M5) with the SAM (T4). No mission is assigned to the tanks (T2) (see Figure 6).

Figure 6. Visual Representation of Model Run 1 Results. The Warthogs (M1) are paired with the cave (T3), The Prowler (M5) is paired with the SAM (T4), and the F/A-18Fs (M4) are paired with the moving trucks (T1).

	m1.t1	m1.t2	m1.t3	m1.t4	m2.t1	m2.t2	m2.t3	m2.t4	m3.t1	m3.t2
priority t	1	2	1	1	1	2	1	1	1	2
precedence t	10	20	1	1	10	20	1	1	10	20
prob_kill wt	0.8	0.6	0.5	0.7	0	0.5	0.4	0.6	0	0.5
num_weapons wm	3	3	3	3	2	2	2	2	2	2
num_targets t	4	6	1	1	4	6	1	1	4	6
time_to_tgt mt	24.0	16.5	36.0	18.0	16.0	11.0	4.0	12.0	15.4	13.7
playtime_remaining m	120	120	120	120	15	15	15	15	45	45
commander weight	90.000	50.000	99.000	99.000	90.000	50.000	99.000	99.000	90.000	50.000
weaps weight	0.701	0.368	0.875	0.973	0.000	0.206	0.640	0.840	0.000	0.206
time to tgt weight	30.119	43.823	16.530	40.657	44.933	57.695	81.873	54.881	46.235	50.373
playtime weight	0.001	0.001	0.001	0.001	22.313	22.313	22.313	22.313	1.111	1.111
Numerical	1	0	1	2	0	13279	115748	101835	0	577
Binary	0	0	1	0	1	0	0	0	0	0

	m3.t3	m3.t4	m4.t1	m4.t2	m4.t3	m4.t4	m5.t1	m5.t2	m5.t3	m5.t4
priority t	1	1	1	2	1	1	1	2	1	1
precedence t	1	1	10	20	1	1	10	20	1	1
prob_kill wt	0.4	0.6	0.9	0.7	0.6	0.9	0	0	0	0.6
num_weapons wm	2	2	2	2	2	2	2	2	2	2
num_targets t	1	1	4	6	1	1	4	6	1	1
time_to_tgt mt	12.0	13.9	18.0	16.0	14.0	16.2	21.6	19.2	16.8	19.4
playtime_remaining m	45	45	25	25	25	25	60	60	60	60
commander weight	99.000	99.000	90.000	50.000	99.000	99.000	90.000	50.000	99.000	99.000
weaps weight	0.640	0.840	0.684	0.331	0.840	0.990	0.000	0.000	0.000	0.840
time to tgt weight	54.881	49.943	40.657	44.933	49.659	44.486	33.960	38.289	43.171	37.833
playtime weight	1.111	1.111	8.208	8.208	8.208	8.208	0.248	0.248	0.248	0.248
Numerical	3863	4614	20538	6096	33898	35790	0	0	0	780
Binary	0	0	1	0	0	0	0	0	0	1

Table 1. Components of the Reward Coefficients for Model Run 1. For each pairing, we show the value of each term in the reward coefficient, and then summarize the numerical results of multiplying the first five terms, and the final result of the three binary terms representing logical conditions of the pairing. The final reward coefficient is the product of these two numbers.

In Table 1, we provide the reward coefficients for each of the possible pairings in this scenario, the only pairings in *P* are the Warthogs (M1) and the cave (T3), The F/A-18Fs (M4) and the trucks (T1), and the Prowlers (M5) and the SA-2 (T4). The highest reward value in the model run is 115,748 and it comes from pairing a pair of F/A-18C Hornets (M2), with an enemy cave (T3). However, this pairing is eliminated because the

Hornets are assigned to a CAS mission and the cave requires aircraft on an INT mission. Additionally, the Hornets are armed with JDAMs (which are not standoff weapons) and the cave is located in a SAM ring that requires standoff weapons.

The highest reward value of the feasible pairings is 20,538 and corresponds to two F/A-18F Hornets (M4) paired with four trucks moving down a road (T1). The Hornets are on a CAS mission and the trucks are a CAS target. The trucks are not in a SAM ring so the lack of a standoff weapon (which the Hornets lack) is not a problem, and each laser-guided bomb they carry has a 0.9 probability of kill on a moving truck. For these reasons, the model recommends pairing the Hornets and the trucks.

The next-highest reward value that is feasible and greater than zero is 780 from the pairing of an E/A-6B Prowler (M5) and a SAM (T4). Although The SAM is in a SAM ring (in this case, its own), the weapons of the Prowler have adequate standoff and a high kill probability against this target.

Finally, the model recommends pairing two A-10 Warthogs (M1) and the previously discussed enemy cave (T3). The reward function for this pairing only has a value of 1, but the reward value is low because the Warthogs have 120 minutes of playtime remaining. Using aircraft with that much playtime would probably be wasteful if other capable assets were available. However, there are no other assets that can hit the cave, so the Warthogs are the best aircraft available to hit that target and, in this scenario, should probably be assigned to strike it.

For a second scenario, to show how pairings change as data inputs change, we remove the SAMs defending the cave (T3); see Figure 7.

Figure 7. A Visual Representation of Model Run 2 Results. Because the SAMs are removed from the cave (T3), the Falcons (M3) can now be used to strike the cave (T3) instead of the Warthogs (M1). The Falcons (M3) are a better pairing because they have less playtime than the Warthogs (M1) and are comparable in every other way.

As can be seen, the solution stays the same except for the mission pairing to the cave. Instead of sending the Warthogs (M1) to strike the cave (as the previous solution did), the model now sends two F-16 Falcons (M3) armed with JDAM to strike the cave. This is a better pairing. With the SAMs defending the cave, the Falcons could not be used because their weapons did not have the standoff to strike the target. With the SAMs gone, the standoff requirement is reduced to zero. The Falcons are slightly closer to the cave than the Warthogs, and the Falcons have significantly less playtime than the Warthogs. The kill probabilities against a cave for the weapons of the Falcons and Warthogs are comparable. The reward value for pairing the Falcons and the cave is 3,863. The reward value for pairing the Warthogs and the cave is 1. In this case, the pairings were comparable except for the playtime differentials, and the model adjusted well to the change.

The speed of RASP was tested using a GAMS file with 100 strike packages, 100 targets (97 of which were in SAM rings), 100 different weapon types, and 10 different mission types. This problem would take weeks to solve manually. RASP solved it in 0.016 seconds.

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V. CONCLUSIONS AND OPPORTUNITIES

A. SUMMARY

The existing U.S. system of pairing aircraft to targets is slow, inefficient, and inconsistent. This thesis has described RASP (Rapid Air Strike Pairing), a decision aid for pairing strike packages and targets for Airborne Battle Managers. RASP is made up of a GAMS model and data that represent a given strike mission scenario with multiple missions and multiple targets, and solves for the optimal pairing of strike packages to targets given a quantitative measure of the quality of each such pairing. RASP is the only decision support tool we are aware of for making optimal real-time pairings at the Airborne Battle Manager level. RASP solves almost instantly, with even large example problems (with hundreds of packages and targets) solving in just fractions of a second.

Although we developed RASP to improve the response time for requests, it would be a mistake to try to completely automate the system and remove the operator. ABCC is too dynamic a mission to be done well without a human in the decision loop, and from our own experience we know that there are many situations in which a planner must modify pairings quickly due to emergent needs, or because of considerations not captured by the parameters in the model. Because of this, RASP is intended to be a decision support tool to provide operators clear guidance in their pairings. Because of its very short execution times, even on large problems, and its adaptability to specific operational requirements, RASP can be used to quickly evaluate several alternative pairings to help operators determine one that best satisfies all mission requirements.

B. FUTURE DEVELOPMENT

The next step in RASP development is to create a useable interface that holds all of the data required for RASP. We have already begun this effort using Microsoft Excel™ with Visual Basic for Applications (VBA) as our programming environment. As part of this effort, we will also add the ability to automatically enumerate all feasible package target pairings, simplifying many of the calculations. Difficulties will include

automating the calculation of standoff ranges for each target: complex networks of air defenses can contain targets that are not in range of any one air defense platform, but that are nevertheless unapproachable.

RASP has several potential future uses. RASP is currently run on a stand-alone computer. Networking multiple computers to run RASP would allow the Airborne Battle Management teams to execute the ABCC mission with full situational awareness.

RASP could be expanded to do package-target pairing for both surface and air assets. As forces become more distributed, command and control will become tougher to manage on paper; RASP can be adapted easily to this problem because the fundamental information required to pair surface packages to targets is no different than airborne strike packages. For example, although ships may be slower than aircraft, they still have a speed, a loadout, a standoff range, and a mission type. The only real difference is that ships have much larger playtime (i.e., the time until they next go off-station for a logistics replenishment).

RASP could be populated with information from networks and data links, which would further reduce operator workload, allowing more time to manage the battle. This would require a more significant development effort, however, to create tools that automatically process all of the different messages on these links, extract the relevant information, and then populate the appropriate data tables.

The key to broad acceptance of RASP will be the development of a user interface that is familiar to the operators. We recommend duplicating, via Microsoft Excel™, the system that the operators now use to manage mission data. The existing operator system involving pencil and paper contains all the data RASP requires to run. The only difference is the automatic pairings RASP provides. It is important that any user interface be developed in conjunction with operators because ease of data management is critical to any decision aid that supports the ABCC mission.

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